ANESTHESIA FOR OPEN-HEART SURGERY: ITS CONTRIBUTION TO THE CARE OF THE CRITICALLY ILL*

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THIS memorial to Dr. Barbara Lipton is a fitting occasion to review the benefits that we have derived from specialization in anesthesia. The justification for specialization in pediatrics and obstetrics has passed beyond argument. Whether we must or should provide other surgical specialties with equal treatment is not universally accepted, although more than a decade of personal experience suggests that the knowledge gained easily offsets the dangers of a narrowed horizon.

The critically ill patient brings a remarkable complexity of biochemical, pharmacological, and physiological abnormalities to operation. Fortunately, invasive monitoring—a necessary tool for successful navigation through the poorly charted waters of equally complex surgery —is compelling us to replace clinical impressions with accurate measurement.[4, 24] For those privileged to have participated in this evolution, it is clear that the fruits of this exposure will have extensive consequences for every mode of anesthetic practice.

To give substance to these views, I have chosen three examples from personal experience which provide a spectrum of modified knowledge applicable to all segments of care for the critically ill.

EFFECT OF ANESTHETIC DRUGS ON CARDIAC FUNCTION WITH ANOTHER LOOK AT MYOCARDIAL DEPRESSION

No sooner had we made general anesthesia safe for the patient with severely compromised myocardial function than we were asked to protect the heart with life-threatening ischemia long enough to allow for its surgical revascularization. What was once regarded as an abso-
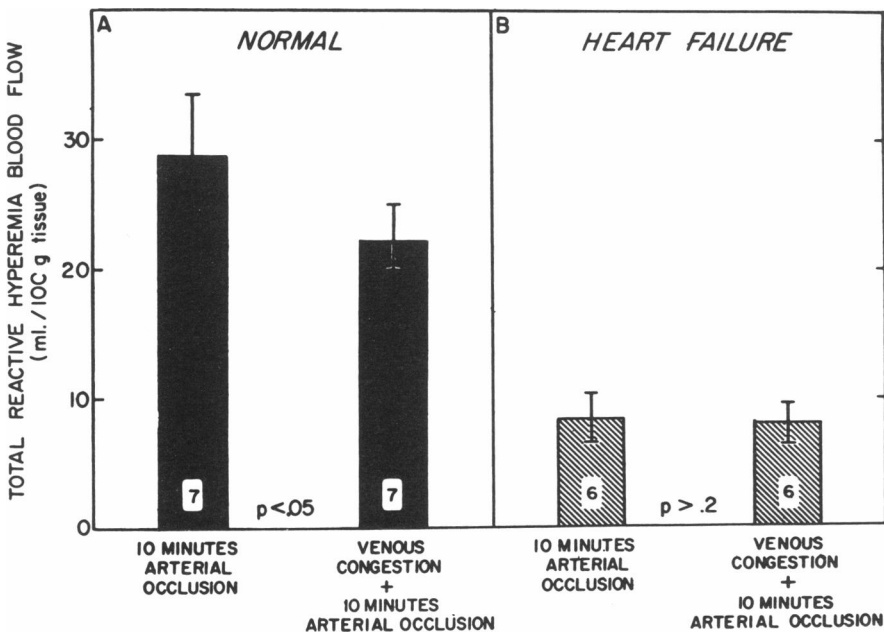
Fig. 1. Reactive hyperemia to arterial occlusion alone and to venous congestion followed by arterial occlusion differed in patients with congestive heart failure (CHF) when compared with normal controls. Both the total and peak reactive hyperemia blood flow were substantially less in patients with CHF because of a reduction in the capacity of resistance vessels. Reproduced by permission from Zelis, R., Mason, D.T., and Braunwald, E.: A comparison of the effects of vasodilator stimuli on peripheral resistance vessels in normal subjects and in patients with congestive heart failure. *J. Clin. Invest. 47*:960-70, 1968.

lute contraindication to general anesthesia—the impending myocardial infarction—has become an astoundingly successful trespass.

Justification for the risk of operation in the presence of rapidly advancing heart disease grew out of the recognition that dramatic recovery and years of useful living do accompany hemodynamic improvement. Thus, the need for anesthetic support under desperate circumstances provided a strong stimulus for the formulation of new criteria applicable to the intraoperative management of the critically ill.

The need to establish appropriate intraoperative conditions in patients with brittle hemodynamic function, accompanied by the need for a smooth transition from the operative to the postoperative phase, resulted in the use of morphine in large quantities (2 to 3 mg./kg. intravenously) as the principal anesthetic drug.* Although this drug

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*Morphine, a drug we have all taken for granted, appears to be becoming scarcer, as are many of our other natural resources.[10]
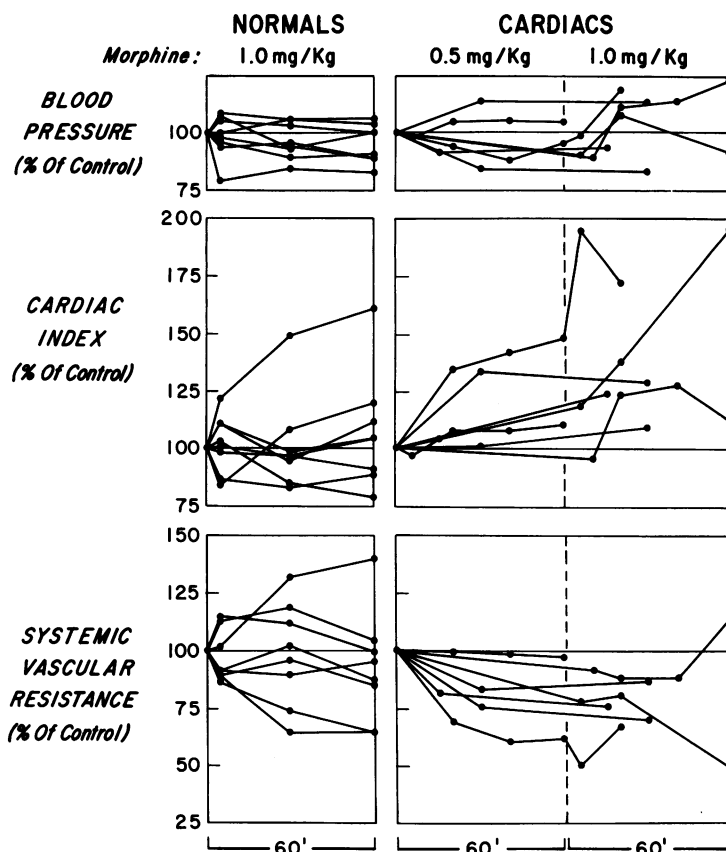
Fig. 2. The administration of morphine (0.5-1.0 mg./kg. intravenously) to patients with heart disease is associated with a consistent rise in cardiac index secondary to a fall in systemic vascular resistance. Patients without known heart disease given morphine (1.0 mg./kg. intravenously) responded in a less predictable manner. Reproduced by permission from Lowenstein, E., Hallowell, P., Levine, F. H., Daggett, W. M., Austen, W. G., and Laver, M. B.: Cardiovascular response to large doses of intravenous morphine in man. *New Eng. J. Med. 281:*1389-93, 1969.

requires no special emphasis because it is only one of the many drugs that we used successfully, a study of its effects[15, 16] drew our attention to the fact that patients in chronic congestive heart failure (CHF) react differently to vasoactive stimuli than do individuals with normal hemodynamic function[12, 29] (Figure 1). Lowenstein et al.[16] demonstrated the applicability of these facts to general anesthesia (Figure 2). These changes, presumably the result of altered electrolyte composition of the arterial wall [28] (Figure 3), represent compensatory mechanisms required for an equitable distribution of blood flow whenever heart disease
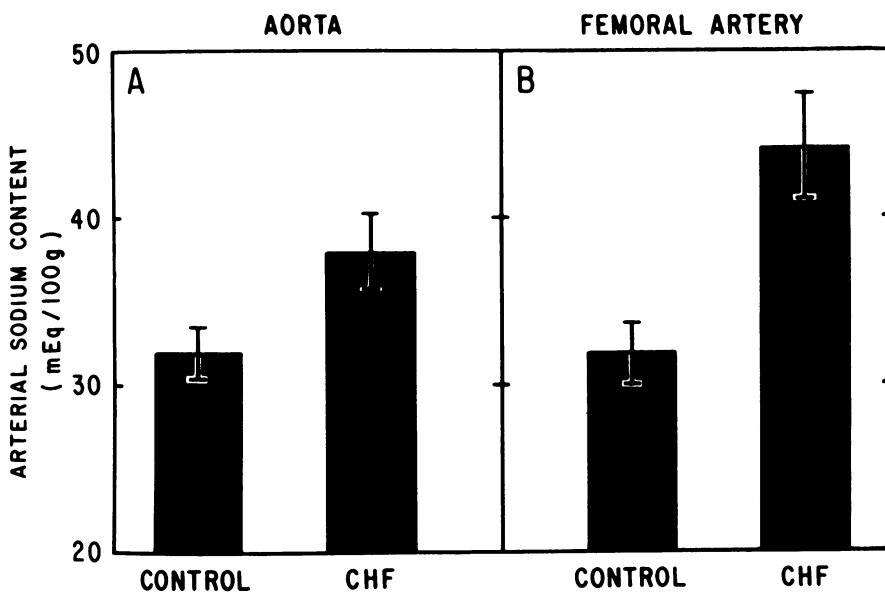
AORTA **FEMORAL ARTERY**

Fig. 3. The sodium concentration measured in segments of aorta (A) and femoral artery (B) obtained from controls and animals with experimentally induced congestive heart failure (CHF). In both instances, sodium retention secondary to congestive heart failure was associated with a substantial rise in arterial wall Na+ concentration. CHF was produced by rapid ventricular stimulation (280 beats/min.) with a pacemaker implanted for 11 to 29 days. All animals had ascites, pleural effusions, peripheral edema, and ventricular diastolic gallop by auscultation. Reproduced by permission from Zelis, R., Delea, C. S., Coleman, H. N., and Mason, D. T.: Arterial sodium content in experimental congestive heart failure. *Circulation* *41*:213-16, 1970.

imposes a limit on the required increase in cardiac output. Other differences which characterize the patient with CHF include a possible centrally mediated digitalis effect[9] and altered drug metabolism secondary to a change in hepatic blood flow.[23, 26] All provide further proof that the measurement of performance during and after operation provides the only means for the evaluation of therapy. For example, Lappas et al.[13] have shown that an inspired nitrous oxide concentration of 50% reduced left ventricular contractility (dp/dt_{max}) when measured after completion of extracorporeal bypass for coronary artery surgery in patients anesthetized with morphine. Associated changes included a rise in pressure in the left but not the right atrium and in pulmonary but not systemic vascular resistance.

On first impression one is likely to interpret the decreased contractility as an adverse reaction. But is this justified?
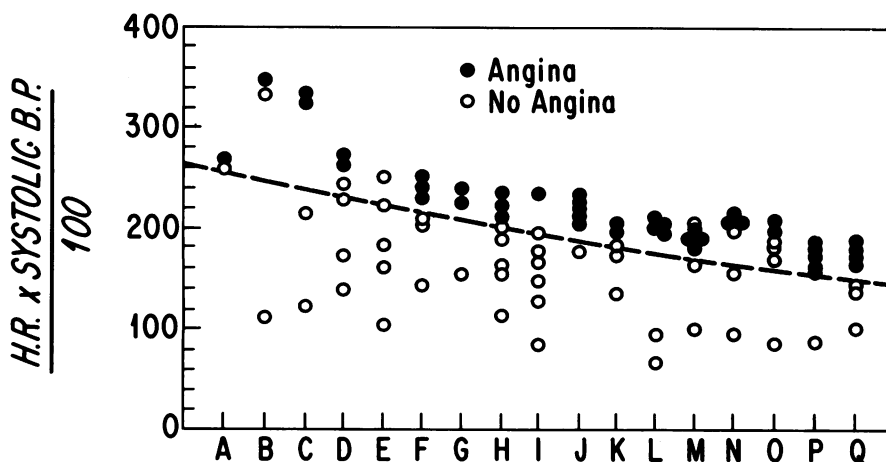
Fig. 4. Patients with known coronary artery disease were stressed by exercise and in some cases by mental arithmetic to determine their anginal threshold. Closed circles denote episodes in which pain occurred; open circles denote episodes in which there was no pain. Each letter denotes one patient. Angina appeared at a level—above a value of the heart rate (H.R.) times systolic arterial blood pressure (B.P.)—which was characteristic for each individual. The dashed line provides an approximate separation between angina and no angina. Reproduced by permission from Robinson, B. F.: Relation of heart rate and systolic blood pressure to the onset of pain in angina pectoris. *Circulation 35:* 1073-83, 1967.

The patient who has coronary artery disease characterized by severe angina pectoris on minimal exertion is exquisitely susceptible to perturbations that alter the balance between the demand for and the availability of myocardial oxygen. In fact, the recognized direct relation between beta-adrenergic activity and myocardial oxygen demand resulted in the use of propranolol, a depressant drug, for the treatment of ischemic pain. Is it not likely that fear implied by the consequences of drug-induced "myocardial depression" may have made us lose sight of the benefits flowing from such information? Stimuli that initiate angina pectoris, including an increase in heart rate or arterial blood pressure, are common after a surgical stimulus during light general anesthesia,[14] yet both are accompanied by a rise in myocardial oxygen demand (Figure 4).

What, then, are the consequences to our care of the patient with symptomatic coronary artery disease? First, we must focus on myocardial oxygen demand[2] and how best to maintain it. Second, we must recognize that reduced myocardial oxygen demand and drug-induced myocardial depression are synonymous and at times are conditions re-

TABLE I. EFFECT OF CHANGING END-EXPIRATORY PRESSURE DURING
MECHANICAL VENTILATION ON CARDIAC OUTPUT
AND LUNG FUNCTION*

End-expiratory pressure (cm. H_2O)	0	5	10	15	10
PaO_2 (mm. Hg.)	58	77	97	168	111
Cardiac index (L/min.M²)	4.59	5.87	6.24	6.71	5.23
FRC (L)	1.62	1.85	2.17	2.63	
% of predicted	35	40	47	57	
Mean airway pressure (cm. H_2O)	9.1	13.2	20.0	22.5	21.8

*The patient, a 52-year-old male weighing 93.1 kg., was in acute respiratory failure secondary to viral pneumonitis.
L = liters, FRC = functional residual capacity.

quired for survival. Third, we should note that endocardial ischemia is difficult to recognize during operation and usually escapes detection by standard limb-lead electrocardiography.[6]

Bland and Lowenstein[1b] have used the experimental model described originally by Maroko et al.[18] to demonstrate the protective effect of halothane anesthesia following acute occlusion of the left anterior decending coronary artery in the dog. Careful multiple-lead mapping of the surface electrocardiogram around the area supplied by this vessel permits quantification of the resultant ischemia when all ST elevations are summated. With transient occlusion, the ST segments return quickly to baseline once blood flow is reestablished. Thus, the protective effect of drugs is assessed by the reduction in summated ST changes following transient occlusion. If the animal is anesthetized with halothane, protection is readily apparent and the myocardial depressant effect of halothane assumes a positive character. Translated to the clinical situation, halothane or any anesthetic that exhibits a mechanism of action similar to beta-blockade (as, for example, nitrous oxide) may be a drug of choice for the patient with severe coronary artery disease.

Attia et al.[1a] found that left ventricular dysfunction characterized by a significant rise in right atrial, pulmonary artery mean, and capillary wedge pressures followed aortic occlusion for excision of an abdominal aortic aneurysm, and appeared only in patients with a history suggestive of coronary artery disease. Controlled myocardial depression is probably beneficial in this setting, but its proper application will require improved methods of intraoperative monitoring of the distribution of
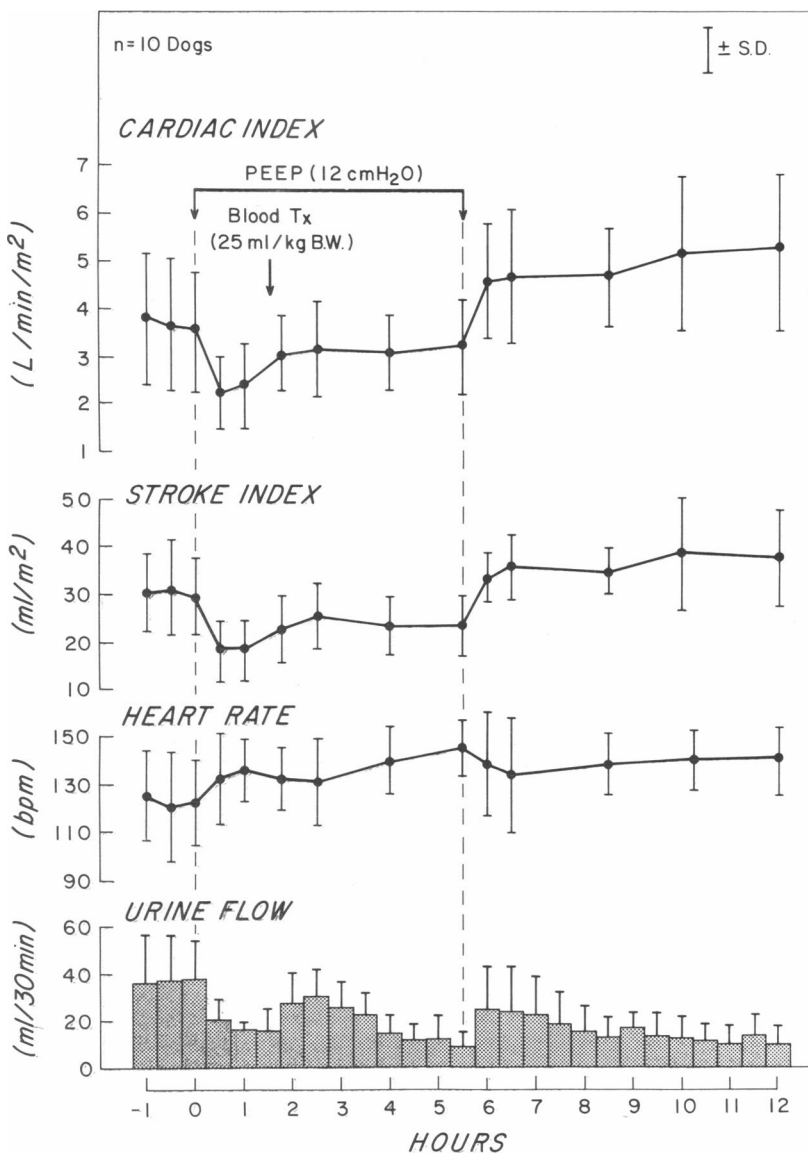
Fig. 5a. Dogs anesthetized with 0.5% halothane and paralyzed were ventilated mechanically with 12 cm. H_2O positive end-expiratory pressure (PEEP). After approximately 90 minutes of ventilation, blood volume was increased by transfusion of 25 ml./kg. body weight whole blood with a resultant rise in cardiac index and stroke volume index. Upon removal of PEEP, cardiac index rose above control levels and remained elevated throughout the period of study.
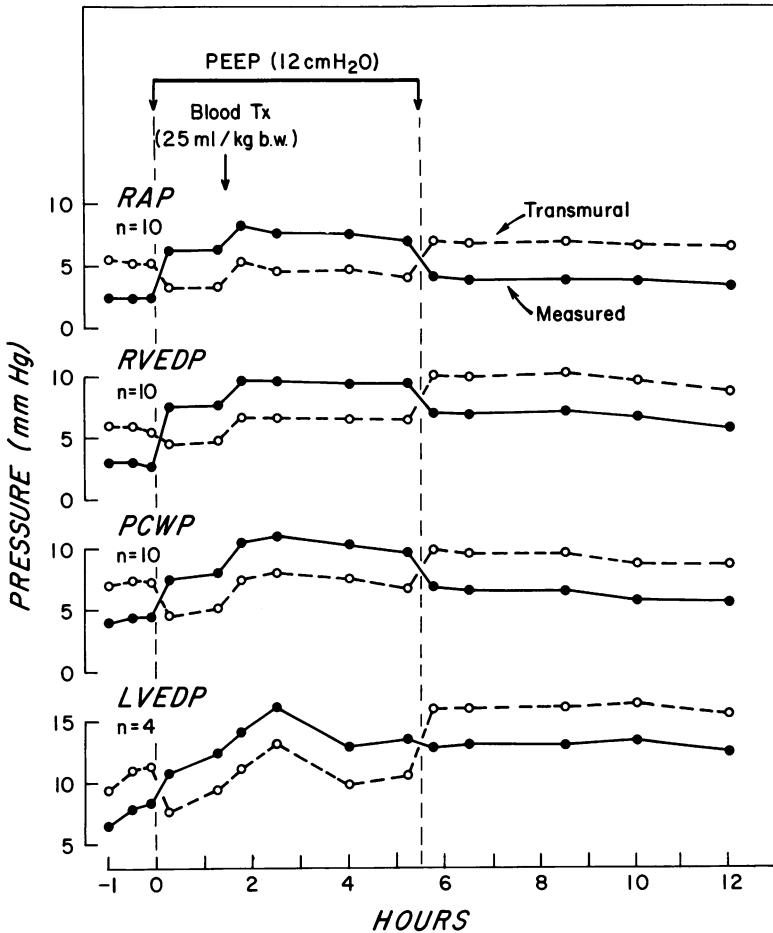
Fig. 5b. Same conditions as in Figure 5a. Measured pressures refer to atmospheric pressure. Transmural pressures were calculated as the algebraic difference between cavitary and pleural pressures, both measured relative to atmospheric pressure. Following addition of PEEP, transmural pressures fell and rose to control levels upon transfusion with a further increase upon removal of PEEP. RAP = right atrial pressure, RVEDP = right ventricular end-diastolic pressure, PCWP = pulmonary capillary wedge pressure, LVEDP = left ventricular end-diastolic pressure. Reproduced by permission from Qvist, J., Pontoppian, H., Wilson, R. S., Lowenstein, E., and Laver, M. B.: Hemodynamic response to mechanical ventilation with PEEP: The effect of hypervolemia. *Anesthesiology 42:45-55, 1975.*

myocardial blood flow. The standard limb leads of the electrocardiogram have little to offer in this respect.[6]

INCREASED AIRWAY PRESSURE, VENTILATOR THERAPY, AND MYOCARDIAL FUNCTION

Several years ago, while evaluating the hemodynamic response to added positive end-expiratory pressure (PEEP) during mechanical ventilation (MV), Falke et al.[8] noted an occasional paradoxical increase in cardiac output with each increment in airway pressure (Table I). Conversely, a trial at spontaneous respiration was associated with a decrease in cardiac output not attributable to abnormal oxygenation since arterial PO_2 fell only slightly. Although several explanations have been proposed for this phenomenon, none have been satisfactory, including a hypothesis based upon the attendant increased work of breathing."

A possible explanation became apparent during a recent study by Trichet et al.,[27] which examined hemodynamic performance and blood-gas exchange during mechanical ventilation with and without PEEP following aortic (AVR) and mitral valve (MVR) replacement. Addition of 10 cm. H_2O PEEP following AVR was associated with a predictable decrease in cardiac output; a similar maneuver following MVR resulted in no significant change in blood flow.

All patients in the MVR group had pulmonary hypertension and substantially higher right and left sided filling pressures secondary to more aggressive blood-volume replacement intended to maintain an adequate cardiac output. Thus, in patients with prominent right ventricular failure and an elevated right ventricular afterload, a reduction in airway pressure was not followed by an increase in blood flow. In the course of parallel studies, Qvist et al.[20] subjected experimental animals to MV with PEEP and noted that the expected decrease in cardiac output as well as right and left atrial transmural pressures could be restored to control values by appropriate blood transfusion of 25 ml./kg. body weight. (Figures 5a and 5b). Removal of PEEP resulted in a rise in cardiac output and transmural pressures above control, a change which persisted throughout the period of study. This provided a clue to the paradox.

Patients who require high airway pressures or mechanical ventilation with PEEP frequently have a blood volume elevated above normal
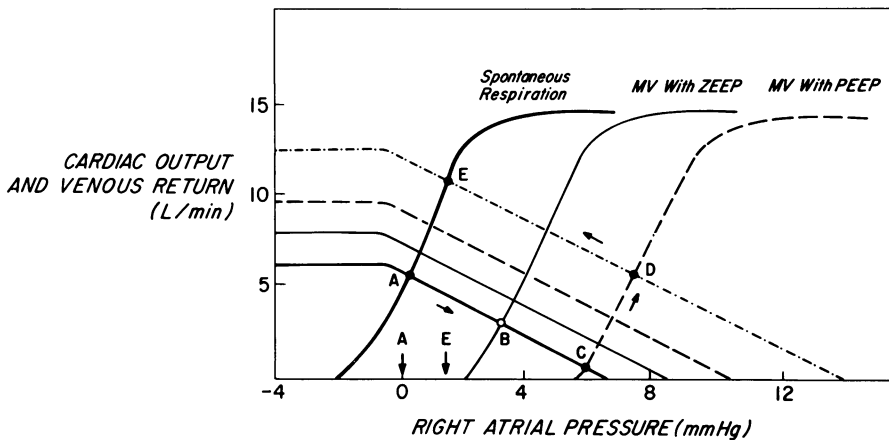
Fig. 6. Effect of an increased blood volume and mechanical ventilation (MV) with zero (ZEEP) and positive end-expiratory pressure (PEEP) on right atrial filling pressure and cardiac output. The cardiac output and venous return curves were drawn according to Guyton.[12b] Point A is the cardiac output-venous return relation with spontaneous respiration. When airway pressure is increased (MV with ZEEP) venous return is diminished and if myocardial contractility remains unchanged, flow decreases to point B. Cardiac output diminishes further with an additional rise in airway pressure (MV with PEEP) and the equilibrium point moves to C. If blood volume is now increased by appropriate transfusions, cardiac output will return to control levels but the venous return will be shifted upward to point D. If airway pressure is reduced by a change to spontaneous respiration, cardiac output will be elevated substantially, as will the right atrial transmural pressure, and equilibrium moves to point E. Reproduced by permission from Laver, M. B., Wilson, R., and Austen, W. G.: *Surgery of the Chest*, 3d ed., Gibbon, J. H., Jr., Sabiston, D. C., Jr., and Spencer, F. C., editors. Philadelphia, Saunders, 1975.

in order to maintain cardiac output at viable levels. On the other hand, acute respiratory failure is frequently associated with an elevated pulmonary vascular resistance and varying degrees of right ventricular failure. If, under these circumstances, the PEEP is removed or the airway pressure is reduced, then translocation of blood volume must take place (Figure 6). A failing right ventricle (RV) on the flat portion of its Frank-Starling curve will exhibit little change in the right ventricular stroke work index (RVSWI) despite the rise in right atrial transmural pressure (Figure 7, arrow on curve I). However, redistribution of blood volume results in a reduction in pulmonary arterial compliance or an increase in RV afterload caused by the limited capacitance of the pulmonary vascular bed. RVSWI decreases as the Frank-Starling curve is shifted to the right (Figure 7, point 2, curve II). An additional decrease in airway pressure, for example an attempt at spontaneous ventilation, will accentuate the problem further. Based on these con-
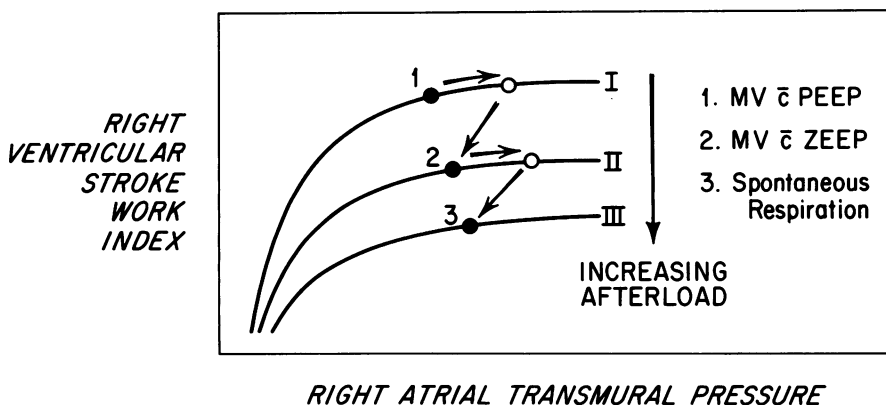
Fig. 7. Right ventricular (RV) Frank-Starling curves drawn for different levels of afterload. Point 1 denotes the relation between RV stroke work index and right atrial transmural pressure (RATP) in a patient with RV failure being ventilated mechanically with positive end-expiratory pressure (MV c̄ PEEP). When PEEP is removed and RV inflow of blood is enhanced (curve I), RATP rises (arrow to right, from solid to open circle) but the redistribution of blood volume results in an increased RV afterload. As a result, RV performance shifts to form curve II and stroke volume decreases with a slight rise in RATP, despite a diminished airway pressure. The problem is intensified further when an attempt is made to have the patient breathe spontaneously (point 3, curve III).

siderations, the success of the weaning process will be dependent on the contractile properties of the RV, compliance of the pulmonary arteries, venomotor tone, and blood volume.

Many have found that weaning from ventilator therapy may be difficult despite a clear chest x ray or appropriate arterial blood gases. At times a trial at spontaneous ventilation is accompanied by increasing agitation or the development of an arrhythmia despite little or no change in vital signs or blood-gas exchange. In both situations right ventricular failure must be suspected.

However, the problem does not stop here. Acute changes in right ventricular volume and performance are known to influence left ventricular geometry and function, just as changes in coronary perfusion pressure have been demonstrated to influence behavior of the stressed right ventricle.[3] Therefore, the rise in both right and left atrial pressures may only reflect this interdependence (Figure 8).[5, 17, 19, 25] Therapeutically, then, the decrease in cardiac output following a diminution in airway pressure can be approached in one of several ways: If right ventricular failure is suspected, weaning from ventilator therapy must precede weaning from ongoing myocardial inotropic therapy. If car-
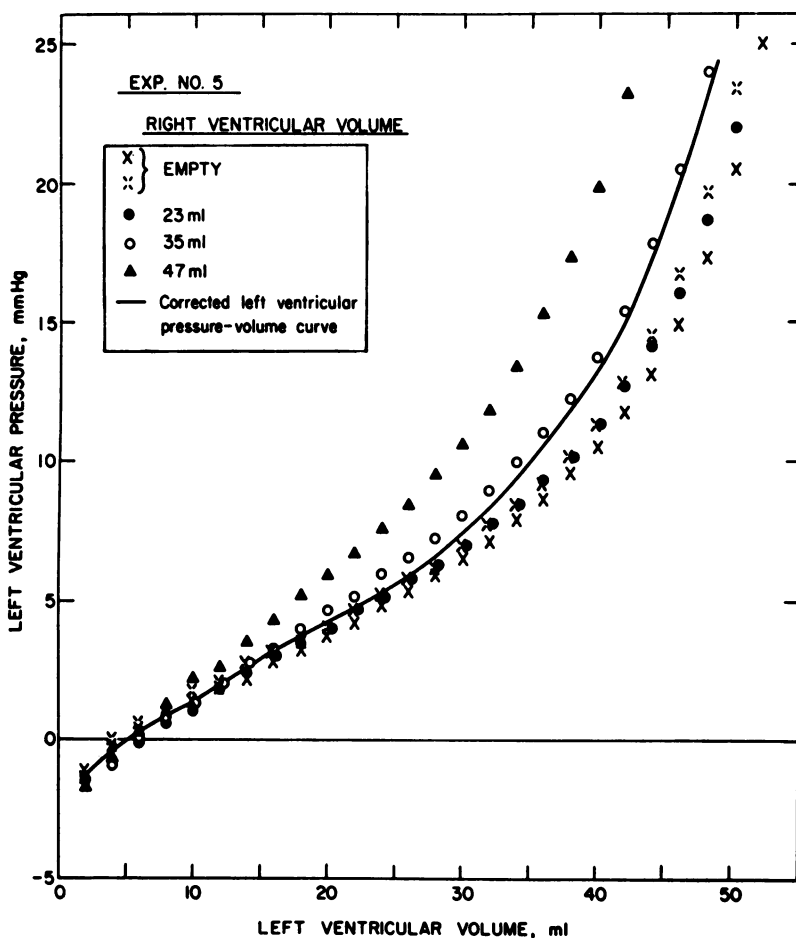
Fig. 8. Effect of changes in right ventricular volume (insert) on left ventricular distensibility, i.e., relation between left ventricular pressure and volume. The solid line represents the relation found to exist during blood infusion in the beating heart, corrected for the influence of right ventricular filling. All other curves were derived from incremental filling of the right ventricle in the potassium-arrested heart. Left ventricular distensibility was reduced markedly as right ventricular volume rose at high left ventricular pressures. Reproduced by permission from Taylor, R. R., Covell, J. W., Sonnenblick, E. H., and Ross, J., Jr.: Dependence of ventricular distensibility on filling of the opposite ventricle. *Amer. J. Physiol. 213*:711-18, 1967.

diac output decreases upon trial at spontaneous respiration, then increased inotropic support must be considered. If right and left ventricular filling pressures are noted to rise following a reduction in airway pressure, then pharmacological phlebotomy or vasodilatation, e.g., with sodium nitroprusside, may be required in order to minimize the redistribution of blood volume.

TABLE II. DETERMINANTS OF MYOCARDIAL OXYGEN CONSUMPTION OF
LEFT AND RIGHT VENTRICLE

1) Tension development
2) Contractile state
3) Heart rate

The recent success attributed to intermittent mandatory ventilation (IMV) for successful weaning[7] may represent another method for gradual hemodynamic readjustment to the consequences of a changed airway pressure. Clearly, the lesson learned from the patient with operable heart disease once more finds applicability in therapy other than open-heart surgery.

HEMODYNAMIC CONSEQUENCES OF AN ALTERED PERIPHERAL VASCULAR RESPONSE: WHITHER VASODILATORS

The major determinants of myocardial oxygen consumption are listed in Table II. Since increased arterial tone or decreased arterial compliance characterizes the basal state for congestive heart failure, the improvement of myocardial function may be achieved by a reduction in afterload.[12] This is particularly critical when myocardial function is compromised by acute ischemia caused by infarction or prolonged extracorporeal bypass.

The benefits of vasodilation were recognized early by the clinical anesthetist experienced with spinal anesthesia. Recently these prin-

Fig. 9. Effect of vasodilator therapy in a patient with severe pulmonary hypertension secondary to mitral valve disease; mitral valve replacement (MVR) was performed for mitral regurgitation and pulmonary hypertension. Pulmonary artery systolic pressure measured via a Swan-Ganz catheter varied from 115 to 130 mm. Hg prior to induction of anesthesia. Because of the high pulmonary vascular resistance, the administration of phentolamine was started shortly after termination of extracorporeal bypass (post bypass) at a rate of 100 μg./min. Phentolamine was chosen over nitroprusside because at the infusion rate of 100 μg./min. (6 mg./hour) alpha-blockade can be achieved gradually without a drop in blood pressure. Pulmonary artery (PA) alternans indicative of right ventricular failure was present before and after extracorporeal circulation (lower-right-hand panel). The hypertension noted postoperatively (post-op) is not unusual when the increase in arterial impedance is associated with a reflex increase in cardiac output. It does not respond to additional phentolamine. Control of arterial blood pressure was achieved by the addition of a sodium nitroprusside infusion (30 μg./min.) Phentolamine infusion was continued for 72 hours. The patient survived and was discharged 12 days after the operation.

MVR FOR MITRAL REGURGITATION AND PULMONARY HYPERTENSION
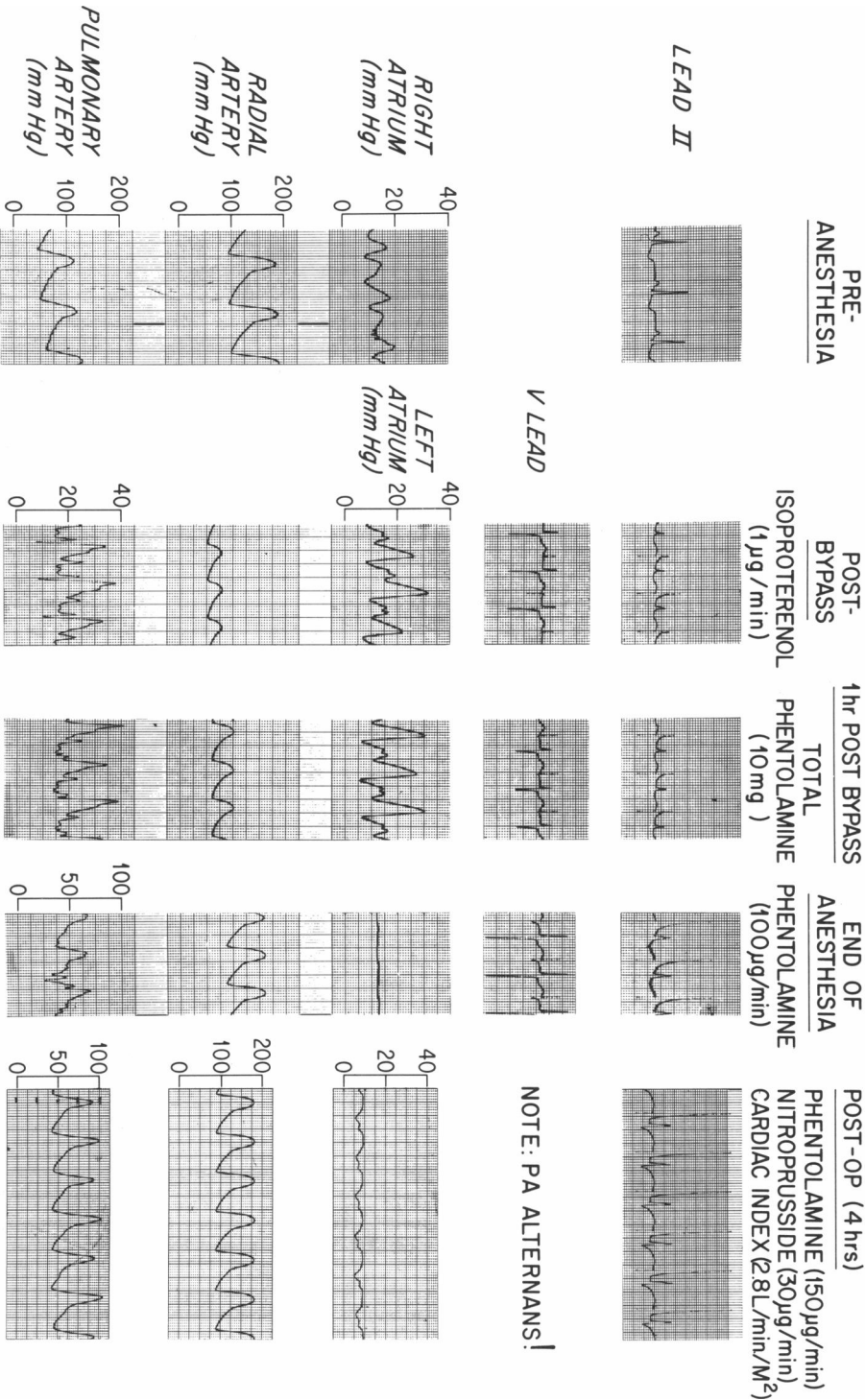
ciples have found favor for treatment of congestive heart failure[11] or acute myocardial infarction,[22] and preliminary experience has been promising. In brief, an increase in venous or arterial compliance reduces either preload or afterload, thereby decreasing myocardial oxygen demand to bring demand more closely in line with a limited supply.

Our experience in patients with coronary artery disease suggests that the careful monitoring of filling pressures in conjunction with vasodilator therapy[14] and controlled levels of myocardial depression represents a substantial advance toward lowering mortality after surgery following recent myocardial infarction. Also, as shown by Attia et al.,[1a] judicious use of vasodilators such as sodium nitroprusside following cross-clamping of the aorta is uniformly successful in lowering pulmonary capillary wedge pressure in patients with known coronary artery disease.

In view of the altered peripheral vascular reactivity described earlier for the patient with chronic congestive heart failure and the increased myocardial oxygen demand elicited by an increased ventricular afterload, intraoperative vasodilation with drugs more potent than the available anesthetic drugs is in order. Alpha-adrenergic blockers such as phentolamine appear to have a specific value whenever control of arterial compliance with an associated reflex rise in cardiac output is desired, e.g., in pulmonary hypertension secondary to mitral valve disease (Figure 9).

Regardless of how we view the controversy concerning the ultimate contribution of coronary artery surgery to longevity, there is little doubt that the impetus for a study of the relation between myocardial blood flow and heart function has been enormous. Whether we, as anesthetists, can apply it to patients with diseased hearts who require other types of surgery will depend on the success of clinical investigation in the sick. An adequate understanding of disease can be achieved only in the habitual presence of disease, which is made possible only by a continued specialization within anesthesia. Judged by the benefits provided so far, it should be an exciting future indeed.

POSTSCRIPT

In closing, I must express my appreciation for this opportunity to present the Barbara Lipton Memorial Lecture. Many have admired Dr. Lipton's resoluteness to provide an outstanding example of clinical ex-

cellence; few have come up to her standards. In these difficult times good anesthetic practice, like the world food problem and coronary blood flow in coronary artery disease, share a common dilemma: a limited supply and an unlimited demand. The likes of Dr. Lipton are in limited supply indeed. Life was a stage upon which she displayed her beauty, charm, and dedication to scholarly medicine to the very end. As in a good play, the end came much too soon.

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